CIGS SOLAR MODULES: PROGRESS IN PILOT PRODUCTION, NEW DEVELOPMENTS AND APPLICATIONS

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ABSTRACT: $Cu(In,Ga)Se_2$- (CIGS) based thin-film solar module technology is a very promising candidate for cost-effective PV module production because it combines high-quality products with large-area production technology.

The pilot production at Wuerth Solar is progressing steadily. Best modules on the standard size of 60 cm x 120 cm reached 85 W_P, which corresponds to nearly 13% aperture-area efficiency. The average module efficiency is 11% to 11.5%. The overall yield of the pilot line could be increased and stabilised to high values. With current developments, the assumptions used as a basis for the cost estimations published in [1] have become reality.

Besides the pilot line activity, which is based mainly on standardised processes, ZSW is developing further material and process improvements. ZSW and Wuerth Solar scaled up the in-line production technology for the in-line co-evaporation of CIGS over 120 cm deposition width in the laboratory in order to improve the throughput by a factor of two. Future-oriented research topics at ZSW include developing flexible modules and Cd-free buffer layers.

Outdoor results with CIGS modules in various applications show high energy ratings and performance reliability. Furthermore, different CIGS modules are being developed for building integration and other applications.

Keywords: $Cu(In,Ga)Se_2$, Manufacturing and Processing, Qualification and Testing

1 INTRODUCTION

What is a good solar cell concept? For power production, a major factor is a high efficiency-to-cost ratio. The module efficiency should be high, and the production costs should be low. Each photovoltaic technology has its own challenges and potential solutions for increasing their efficiency-to-cost ratio. For example, the cost of Si wafer production can be reduced by slicing thinner wafers, ideally with reduced waste during the sawing. Directly producing thin crystalline or polycrystalline silicon layers is another alternative being pursued to reduce materials consumption. Here the challenge is to find an appropriate deposition method which can produce the large grains that are a prerequisite for high efficiencies with crystalline silicon [2]. Amorphous silicon (a-Si) modules, on the other hand, are already cheap to produce and have a low materials consumption. Their efficiency-to-cost ratio needs to be increased by improving the module efficiency, for example by making tandem cells with microcrystalline silicon (µc-Si) [3].

Thin-film technologies based on CdTe and CIGS follow in principle the same strategy to increase their efficiency-to-cost ratio. They both have high potential efficiencies to be developed and transferred to large-scale production. They are both true thin-film techniques and benefit from large-area thin-film deposition, with less waste of materials for larger areas being coated. Costs can also be reduced by accelerating the learning curve for integrated production. It is therefore necessary for investors to already become involved at this point in the development, despite the high risk, in order to realise this high cost-reduction potential.

In this contribution, we present the status of CIGS development in the Wuerth Solar pilot production line. We will describe the progress in the standard production and the performance of the modules under real outdoor conditions. Furthermore, we look to the future with special alternatives being developed at ZSW such as flexible modules, Cd-free buffer layers, and the optimisation of modules for use under various illumination conditions.

2 EXPERIMENTAL

The production of CIGS modules at Wuerth Solar begins with 60 cm × 120 cm sheets of soda-lime glass, which are first cleaned and then sputter-coated with molybdenum. A first patterning step (P1) is performed with a laser scribe to electrically separate the back contacts of the individual cells. The photon-absorbing CIGS layer is then deposited by co-evaporation of the elements, followed by the standard CdS buffer layer deposited in a chemical bath. A second patterning step (P2), a mechanical scribe down to the Mo layer, enables the series connection of the cells in the module. The i-ZnO and ZnO:Al window is subsequently deposited by rf and dc sputtering, respectively. A final patterning step (P3), again a mechanical scribe through to the Mo layer, separates the cells from the front side and completes the monolithic integration of the module. The finishing steps for a commercial product include the bus bar contacts, encapsulation, and framing. For more details see references [4,5,6].

The small-scale pilot line at ZSW follows the same production steps, but is flexible enough to test new developments on a scale up to 30 cm × 30 cm. Several characterisation methods and analytical techniques are also available at ZSW for in-depth studies of the module and materials properties, as well as accelerated lifetime and outdoor testing.

3 PILOT PRODUCTION

3.1 CIGS efficiency road map

Looking at the progress of module efficiencies in the past can help indicate the trend in the future. The first module with CIGS was produced in 1989 at ipe by co-evaporation. A 10 cm × 10 cm module with 13.9 % in 1993 was a star result of the EUROCIS project, followed by 10 % for a 30 cm × 30 cm module at ZSW in 1997. These successes led to the founding of Wuerth Solar in 1999. The first 0.7 m^2 modules were produced in the Wuerth Solar pilot line in 2001 with an average of 8 % efficiency. The module efficiencies have since increased to 9 – 10 % in 2002, 10 – 11.5 % in 2003, and currently 12 % in 2004. Following this trend, it is reasonable to expect module efficiencies of 14 % in two to four years, and 15 % six to eight years from now. Figure 1 illustrates this efficiency road map for the average aperture-area module efficiencies for the ZSW 0.07 m^2 modules and, after upscaling by a factor of 10, the standard 0.7 m^2 modules produced at Wuerth Solar. It is readily apparent that the assumptions made seven years ago (APAS-Music-FM cost study from 1997) are now reality, indicated by the dashed line marking the 12 % efficiency value used as a basis for the study [1].

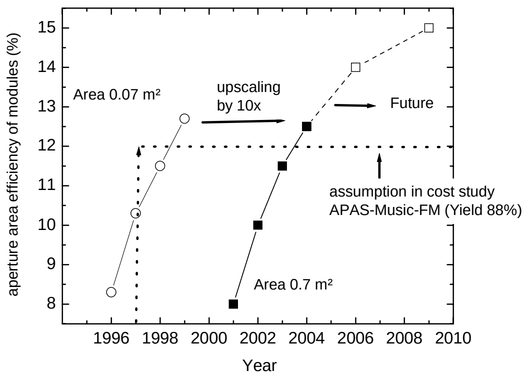

Figure 1: Efficiency road map of average aperture-area efficiencies for 0.07 m^2 ZSW modules and for standard 0.7 m^2 modules from the Wuerth Solar pilot production line, including values expected in the future.

3.2 Status of the pilot line

It was possible to clearly advance the efficiency and yield in the pilot production of large CIGS modules over the last six months. The yield currently exceeds 80 % with an average aperture-area efficiency greater than 11.5 %. It is planned to run the pilot plant at its full capacity of 1.3 MW_p produced module power in 2004, with continuous operation of two 60-cm-wide CIGS coating plants.

Decisive progress was possible through further optimisation and stabilisation of the process control for the CIGS deposition. Figure 2 demonstrates the improved process statistics resulting from the modified feedback control. “Batch A” indicates the typical distribution in the module output power of consecutively CIGS coated modules. Following the successful adjustment of the metal source control program, “Batch B” could be produced with increasing the average output power from 70.7 W_p to 77.7 W_p. At the same time, the standard deviation was reduced from +/– 4.8 W_p to 2.1 W_p.

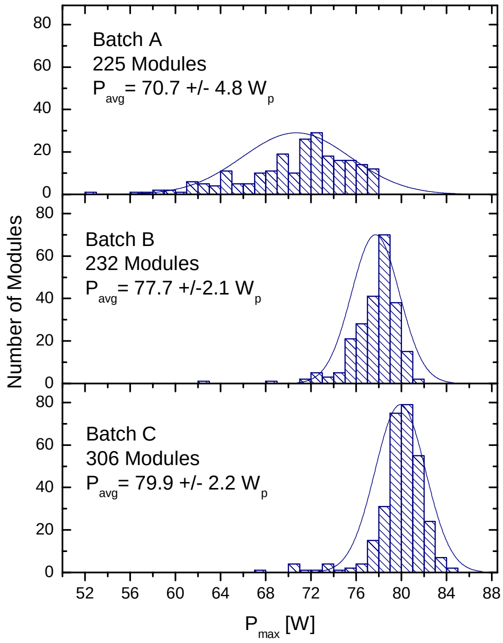

Figure 2: Development of the module power and the process statistics, improved by optimising the process control. The distribution of the module power over Batches A, B, and C becomes more defined and shifts to higher values.

“Batch C” illustrates the results after further optimisation within the production line, especially in contact film deposition and the optimized flow of the process steps. The average module power increased further to 79.9 W_p in Batch C. Batch C demonstrates that consecutively deposited CIGS films and further processed modules can be fabricated without any single module falling below the minimum requirement of 60 W_p electrical power output. The composition of 346 successively coated substrates from Batch C is given in Figure 3. After short adjustment of the process control in the beginning the CIGS film properties are kept within a narrow tolerance for high quality modules.

The desired composition is achieved with an accuracy of +/− 5 % during fault-free operation. The small disturbances described above cause deviations of +/− 10 % in the composition and +/− 20 % in the film thickness and lead to the power distribution as illustrated for Batch C in Figure 2.

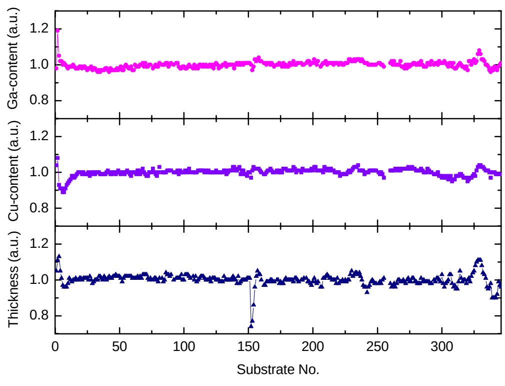

Figure 3: Batch C: XRF composition data for a total of 346 coated substrates. “GGI“: [Ga]/([Ga]+[In])

The average module power of 80 W_p achieved in Batch C corresponds to an aperture-area efficiency of 12.3 %, where the aperture area is defined by the areas of the cells and their interconnections. The average module efficiency is calculated to be 11 % when considering the total area of a framed module with the dimensions of 605 mm × 1205 mm.

3.3 Quality

Besides monitoring the module production line and the module characteristics fresh from the factory, it is necessary to win consumer confidence through certifications, outdoor testing, and the monitoring of installed systems. The Wuerth Solar modules have already been certified according to EN 61646 by the TÜV Rheinland, passing the whole test sequence.

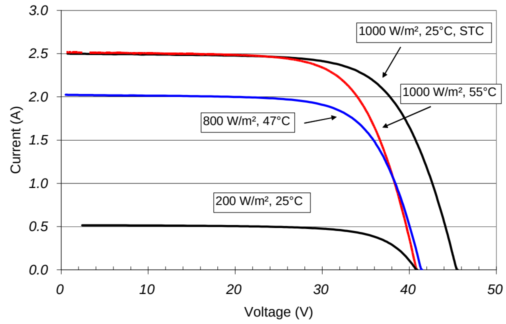

Figure 4: IV characteristics of a typical Wuerth Solar module at realistic illumination/temperature conditions. The fact that the module heats up at higher irradiance levels is taken into consideration. The characteristic at standard testing conditions (STC) is included for comparison.

Since the standard testing conditions of 1000 W/m^2 irradiance at 25 °C do not accurately represent real outdoor operation conditions, the CIGS modules are additionally characterised under realistic illumination / temperature conditions. Realistic outdoor conditions take into consideration that a module subjected to high irradiance levels on a sunny day will also warm up. Hence the characterisation at 55°C for 1000 W/m^2 instead of the standard 25°C, as shown in Figure 4. As expected, the module has a lower open-circuit voltage at the higher temperature, but the current remains at the same level and the curve maintains a reasonable shape. On the other hand, the module temperature will be closer to that of the ambient air on a cloudy day with low irradiance. The curve measured at 200 W/m^2 and 25 °C in Figure 4 represents these conditions. At one-fifth of the irradiance, the module still produces one-fifth of the current. Due to the lower temperature, the open-circuit voltage is at the same 40 V as for a sunny day. The curve at 800 W/m^2 and 47°C gives reasonable intermediate results.

Besides characterisation under realistic outdoor conditions, the modules were also subjected to long-term outdoor testing at the ZSW test field in Widderstall, Germany. Figure 5 presents the temperature-corrected module power measured when the irradiance was 1000 W/m^2. For more information about the outdoor performance of CIGS modules, please see the contribution from Mohring, et al., this conference. Missing data is due to the winter months, when irradiance levels remained below 1000 W/m^2, and for a period between May and August 2003 when the module was dismounted and reinstalled. The outdoor testing indicates stable performance for the entire testing period of over two years.

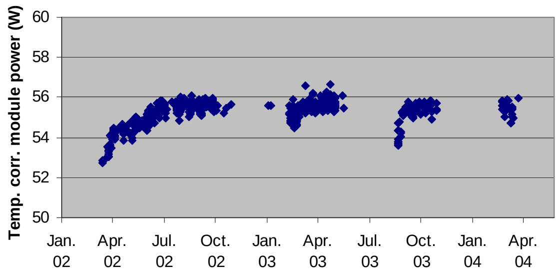

Figure 5: Temperature-corrected module power of a Wuerth Solar module during outdoor testing in Widderstall, Germany. The data were collected at 1000 W/m^2.

Another demonstration of the real-life performance of CIGS modules is available through an interesting project supervised by the Fraunhofer Institute for Solar Energy Systems ISE (Freiburg, Germany), which is monitoring installations with various types of solar cells and from various manufacturers mounted on school roofs in Karlsruhe, Germany. Their website www.karlsruher-sonnendach.de provides more information and current data about these installations.

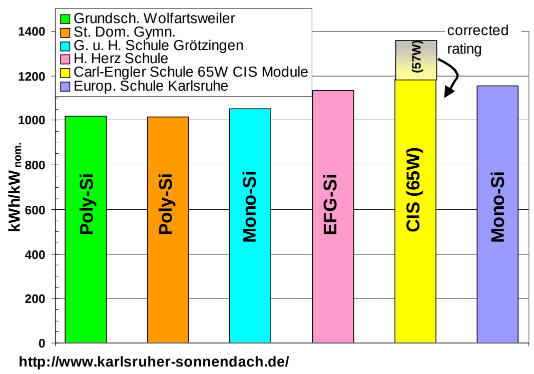

Figure 6: Performance data from 2003 for various PV installations in Karlsruhe, Germany, from monitoring by the Fraunhofer Institute for Solar Energy Systems.

Figure 6 shows the yields for 2003, comparing installations with CIGS modules and conventional Si modules under real operating conditions. The CIGS modules were originally rated at 57 W directly after production, but the extremely high performance ratio indicates that a higher rating is more appropriate. The discrepancy was found to be related to the generally higher performance of CIGS after light soaking. A new measurement performed after illuminating the modules resulted in a corrected rating of 65 W. Even after increasing the rating, the kWh/kW$_p$ yield for the CIGS installation is very high, at the same level as high-quality monocrystalline Si installations.

One reason for the high CIGS power yield is its good performance also under lower illumination conditions, like those often present on cloudy days and in the winter months. The current generation of Wuerth Solar modules are in the 70 to 80 W range and demonstrate excellent low-illumination performance, maintaining at 100 W/m^2 irradiance roughly 95 % of their efficiency measured at 1000 W/m^2, as exhibited in Figure 7. This behaviour has greatly improved since the first modules (≤ 60 W) which only maintained about 75 % of their efficiency under the same conditions. Improvements in the production, resulting in higher shunt resistivities, are responsible for the improved low-illumination performance. At lower intensities under 100 W/m^2, the performance efficiency continues to drop with current modules still performing at about 85 % at 40 W/m^2.

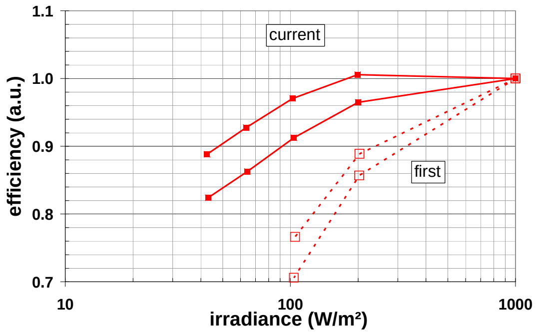

Figure 7: Efficiencies of CIGS modules under varied illumination conditions. The current modules maintain higher efficiencies at lower irradiance intensities.

3.4 Production costs

Increasing the efficiency is not the only approach to improving the efficiency-to-cost ratio, there are also opportunities to reduce the production costs. Standardising the manufacturing equipment and the processes reduces the costs for maintenance and future expansion. A higher degree of automation means that less manual labour is required for production and also simplifies round-the-clock operation.

The productivity can be enhanced by improving the yield and increasing the throughput. The former can be influenced by process optimisation and quality control. Higher cycle times will increase the throughput, as will enlarging the area of modules being processed at the same time. Currently, intense efforts are underway to double the coating width in the CIGS plant to 120 cm, a measure that will effectively double the throughput of the current production. The line sources have already been designed and constructed at ZSW, and initial tests are currently in progress in the world's first 120-cm CIGS coating plant. Calculations and simulations are also being performed for the design of the industrial plant to be constructed at Wuerth Solar by the end of 2004.

Finally, the material costs can be reduced. For example, reactive sputtering of the ZnO window layer would allow the use of cheaper metallic targets. For more details, please refer to Menner, et al., this conference. Furthermore, wasted resources must be systematically identified and, when possible, eliminated.

4 NEW DEVELOPMENTS

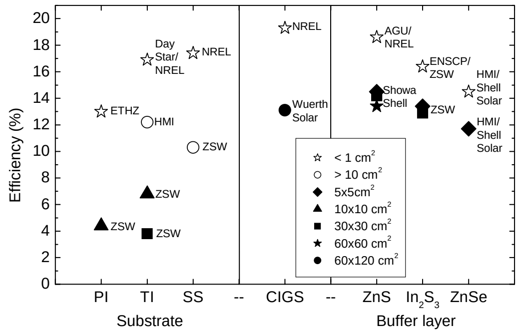

Figure 8: Overview of record cells (open symbols) and modules (closed symbols) on either flexible substrates (polyimide PI, titanium, stainless steel SS) or with a Cd-free buffer layer, compared with the highest, standard efficiencies on glass with a CdS buffer.

Several new developments are being investigated at ZSW with the goal of improving the CIGS production process or to open new markets for CIGS. Two areas are the development of flexible modules on alternative substrates and the development of Cd-free modules. Figure 8 provides an overview of the highest total-area efficiencies reported to date of cells and modules in the standard configuration (glass substrate, CdS buffer) along with the records achieved on alternative flexible substrates (polyimide, titanium, and stainless steel) and the records achieved with Cd-free buffer layers (ZnS, In_2S_3, and ZnSe) [721]. While other laboratories have produced the best flexible cells and Zn-based buffers, ZSW leads the development of flexible CIGS modules and In_2S_3 buffer layers. The following will describe some highlights in the research at ZSW on flexible cells and modules and alternative buffer layers.

4.1 Flexible cells and modules

Substituting the heavy, rigid, and fragile glass substrate with a light and flexible alternative provides multiple advantages. Besides simplifying the transport of the modules, certain applications are enabled like design-compatible product integration and weight-sensitive space applications.

ZSW has produced test cells on polyimide (PI), titanium, and stainless steel foils. The efficiencies for all of these flexible cells have so far always been slightly lower than for reference cells processed at the same conditions on glass substrates coated with an Al_2O_3 Na-diffusion barrier prior to the back contact. Our highest small-area flexible cell efficiency obtained to date is $\eta_{AM1.5} = 11.7$ % with $V_{oc} = 639$ mV, FF = 73.5 %, and $j_{sc} = 25.0$ mA/cm^2 (no AR coating, active area) on a 50-µm-thick PI film. The solar cell suffers mainly from a low current density which must still be improved.

At present, both large cells with a metallic grid on thin Ti foil (4 cm × 8 cm and 25 µm thick) and monolithically integrated modules on 10 cm × 10 cm and 20 cm × 30 cm substrates are being developed at ZSW for space applications. Also, 100-to-150-µm-thick Ti and Cr steel substrates are being investigated for fabricating modules for terrestrial applications. The deposition temperature on metals is comparable to the temperature used for glass substrates (~550 °C). The maximum efficiencies obtained so far at ZSW on flexible small and large-area cells are given in Table 1 (grid design of large-area cells provided by Dutch Space B.V., Leiden, Netherlands).

Table 1: Characteristics of flexible cells on metal foils.

Sample	V_{oc} [mV]	FF [%]	j_{sc} [mA/cm^2]	$\eta_{AM1.5}$ [%]
Ti foil, d = 25 µm, 0.56 cm^2, no ARC	651	74.1	28.5	13.8
Ti foil, d = 25 µm, 27.1 cm^2, no ARC	607	60.0	28.5	10.3
Cr steel, d = 150 µm, 27.1 cm^2, no ARC	585	60.2	29.4	10.3

4.2 Cd-free modules

The standard chemical-bath-deposited (CBD) buffer layer currently employed in CIGS module production has the disadvantages of being a wet process sandwiched between vacuum techniques and of requiring special handling of the cadmium.

ZSW has produced very good results with the atomic layer deposition of In_2S_3 as the buffer layer for 30 cm × 30 cm modules, a process which is vacuum-compatible and Cd-free. However, there appear to be some bottlenecks hindering the upscaling to the module dimensions and throughput required for commercial implementation, and the material costs are high.

A simple exchange of the chemicals in the wet bath process enables replacement of the Cd, e.g. with Zn. Recent experiments with a CBD ZnS buffer layer produced a small cell with 13.9 % efficiency, as shown in Figure 9. Unsolved drawbacks of this buffer layer are that the finished cell requires annealing and light soaking to perform well.

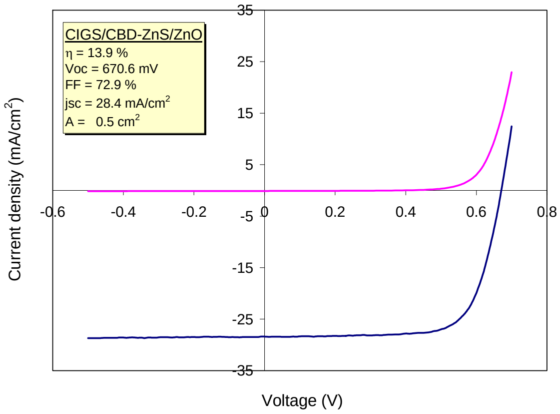

Figure 9: IV curve of a 0.5 cm^2 laboratory cell with a chemical-bath-deposited ZnS buffer layer. It has an efficiency of 13.9 % and an open-circuit voltage of 670 mV.

5 APPLICATIONS

Product visibility and availability will also advance the marketability of CIGS modules. Large installations like the 216 modules on a church roof in Tübingen, Germany (Figure 10) and products like small modules integrated into house numbers (Figure 11) are attention-grabbers that build consumer awareness.

Figure 10: Aesthetic installation of CIGS modules on a church roof, satisfying criteria of monument protection.

Figure 11: CIS module for lighting of house numbers

6 SUMMARY AND OUTLOOK

Photovoltaic modules based on $Cu(In,Ga)Se_2$ provide promising efficiency-to-cost ratios. The development and expansion of the Wuerth Solar production line is progressing well and rapidly so that a future cost-competitive production is probable. Quality and yield are increasing smoothly and CIGS modules are proving themselves in the field.

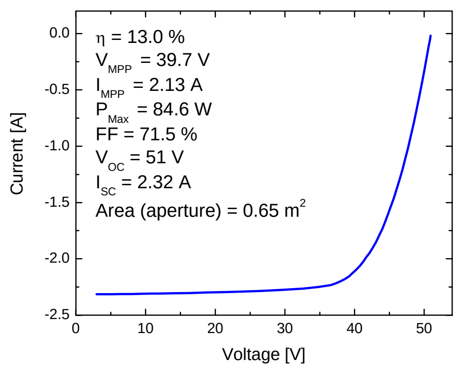

Figure 12: IV characteristic of the current champion 60 cm × 120 cm CIGS module from Wuerth Solar with 13.0 % efficiency.

New developments underway at ZSW will enable future opportunities for further applications and acceptability of the CIGS technology. Finally, to end on a high note and to emphasise the continuing progress in large-area CIGS technology, we present here the latest record IV characteristic in Figure 12. The 60 cm × 120 cm module has an aperture area of 0.65 m^2 and provides 84.6 W with an efficiency of 13.0 %.

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REFERENCES

[1] J.M. Woodcock, H. Schade, H. Maurus, B. Dimmler, J. Springer, A. Ricaud, *Proc. of the 14th European Photovoltaic Solar Energy Conf.*, Stephens & Associates, Bedford, UK, (1997) 857.

[2] M.A. Green, J. Zhao, A. Wang, and S.R. Wenham, "Progress and outlook for high-efficiency crystalline silicon solar cells", Sol. Energy Mater. Sol. Cells 65 (2001) 9.

[3] B. Rech, O. Kluth, T. Repmann, T. Roschek, J. Springer, J. Muller, F. Finger, H. Stiebig, and H. Wagner, "New materials and deposition techniques for highly efficient silicon thin film solar cells", Sol. Energy Mater. Sol. Cells 74 (2002) 439.

[4] M. Powalla and B. Dimmler, "Scaling up issues of CIGS solar cells", Thin Solid Films 361-362 (2000) 540.

[5] M. Powalla and B. Dimmler, "Process development of high performance CIGS modules for mass production", Thin Solid Films 387 (2001) 251.

[6] M. Powalla and B. Dimmler, "Pilot Line Production of CIGS Modules: First Experience of Processing and Further Developments", *Proc.29th IEEE Photovolt. Spec. Conf.* (2002) 571.

[7] K. Ramanathan, M.A. Contreras, C.L. Perkins, S. Asher, F.S. Hasoon, J. Keane, D. Young, M. Romero, W. Metzger, R. Noufi, J. Ward, and A. Duda, "Properties of 19.2% Efficiency ZnO/CdS/$CuInGaSe_2$ Thin-Film Solar Cells", Prog. Photovolt: Res. Appl. 11 (2003) 225.

[8] J. Kessler, J. Wennerberg, M. Bodegård, and L. Stolt, "Highly efficient $Cu(In,Ga)Se_2$ mini-modules", Sol. Energy Mater. Sol. Cells 75 (2003) 35.

[9] A.N. Tiwari, M. Krejci, F.-J. Haug, and H. Zogg, "12.8% efficiency $Cu(In,Ga)Se_2$ solar cell on a flexible polymer sheet", Prog. Photovolt: Res. Appl. 7 (1999) 393.

[10]F. Kessler, K. Herz, M. Powalla, M. Hartmann, M. Schmidt, and H.W. Schock, "Flexible and monolithically integrated CIGS-Modules", Mat. Res. Soc. Symp. Proc. 668 (2001) H3.6.1.

[11] J.R. Tuttle, A. Szalaj, and J. Keane, "A 15.2% AM0/1433 W/kg thin-film $Cu(In,Ga)Se_2$ solar cell for space applications", *Proc. 28th IEEE Photov. Spec. Conf.* (2000) 1042.

[12] A. Neisser, C.A. Kaufmann, M.A. Kroon, R. Klenk, and R. Scheer, „Flexible $Cu(In,Ga)Se_2$ Solar Cell for Space Applications", *Proc. 3rd World PV Conf.* (2003) 458.

[13] M. Powalla and B. Dimmler, "Large-Area CIGS Modules: Pilot Line Production and New Developments", *Techn. Digest of the 14th International Photov. Science and Engin. Conf.*, Bangkok (2004) 513.

[14] M.A. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon, and R. Noufi, "Progress toward 20% efficiency in Cu(In,Ga)Se2 polycrystalline thin-film solar cells", Prog. Photovolt: Res. Appl. 7 (1999) 311.

[15] F. Kessler, D. Hermann, and M. Powalla, "Approaches to Flexible CIGS Thin-Film Solar Cells", presented at the EMRS in Strasbourg, to be published in Thin Solid Films (2004).

[16] M.A. Contreras, T. Nakada, M. Hongo, A.O. Pudov, and J.R. Sites, "ZnO/ZnS(O,OH)/$Cu(In,Ga)Se_2$/Mo Solar Cell with 18.6% Efficiency", *Proc. 3rd World PV Conf.* (2003) 570-574.

[17]K. Kushiya, "Progress in large-area Cu(InGa)Se2-based thin-film modules with the efficiency of over 13%", 3rd World PV Conf. (2003) 319.

[18] N. Naghavi, S. Spiering, M. Powalla, B. Cavana, and D. Lincot, "High-Efficiency Copper Indium Gallium Diselenide (CIGS) Solar Cells with Indium Sulfide Buffer Layers Deposited by Atomic Layer Chemical Vapor Deposition (ALCVD)", Prog. Photovolt: Res. Appl. 11 (2003) 437-443.

[19] S. Spiering, D. Hariskos, M. Powalla, N. Naghavi, and D. Lincot, "Cd-free $Cu(In,Ga)Se_2$ thin-film solar modules with In_2S_3 buffer layer by ALCVD", Thin Solid Films 431-432 (2003) 359-363.

[20] W. Eisele, A. Ennaoui, P. Schubert-Bischoff, M. Giersig, C. Pettenkofer, J. Krauser, M. Lux-Steiner, S. Zweigart, and F. Karg, "XPS, TEM and NRA investigations of Zn(Se,OH)/$Zn(OH)_2$ films on $Cu(In,Ga)(S,Se)_2$ substrates for highly efficient solar cells", Solar Energy Materials & Solar Cells 75 (2003) 17-26.

[21] A. Ennaoui, S. Siebentritt, M.C. Lux-Steiner, W. Riedl, and F. Karg, "High-efficiency Cd-free CIGSS thin-film solar cells with solution grown zinc compound buffer layers", Solar Energy Materials & Solar Cells 67 (2001) 31-40.